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The influences of mineral fertilization and crop sequence on sustainability of corn production in northeastern China

Qiang Ma, Wan-Tai Yu*, Chun-Ming Jiang, Hua Zhou, Yong-Gang Xu

Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, PR China

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ABSTRACT

A sustainable agricultural production can be divided into three aspects, namely high crop productivity, stable yield and improved soil quality. The long-term effects of mineral fertilizers and crop sequence on corn (*Zea mays* L.) productivity, yield stability and soil fertility properties were studied on an Alfisol in northeastern China, based on a consecutive 18-year field trial. The results showed that the balanced mineral fertilization and preceding soybean could increase and stabilize the corn yield, and the influence of fertilization on yield performance was more obvious than crop sequence. In all treatments, soil organic carbon (SOC) and total N (TN), which were the key soil properties to improve corn yield and stability, declined from the initial level. Application of N tended to cause soil acidification, but no significant reduction in corn yield has been observed due to pH decrease over the study period. The decrease in SOC, TN and soil pH, however, were probably potential threats to sustainable development of agriculture. Furthermore, the relationship between yield and relative aridity index was statistically significant ($P < 0.01$), and the optimum range of aridity index for high and stable yield was from 0.89 to 1.11 in this region. Water supply in April plays a critical role in achieving high and stable yield, especially for the low fertility treatments. Overall, our results provided insights for nutrients and water management in sustainable agriculture.

1. Introduction

Corn (*Zea mays* L.) is the main crop in North China, accounting for 58% of the total cereal area (National Bureau of Statistics, 2008) and is an important staple crop for food, livestock feed and biofuels (Landis et al., 2008; Edgerton, 2009). Therefore, corn productivity is important to ensure the country's food and energy security (Zhu and Chen, 2002). Although great achievements in corn production have been made through high yielding varieties, intensification of cropping and increased input of mineral fertilizers, many beneficial agricultural practices are gradually being abandoned, such as crop rotation, intercropping and nutrient recycling (Ma et al., 2002; Crews and Peoples, 2004). A series of environmental issues have been induced due to over-reliance on synthetic fertilizers, and they are the grand challenges to agricultural sustainable development (Ju et al., 2009; Miao et al., 2011).

The important purposes of sustainable agriculture are to ensure high yield, yield stability and soil fertility (Piepho, 1998). A number of reviews have been published on the results of evaluating cultivation methods capable of sustaining both crop yields and soil quality (Jenkinson and Rayner, 1977; Ladha et al., 2003; Yan and Gong, 2010; Duan et al., 2011), but analyzing stability of crop yields faced difficulty using the conventional analysis of variance approaches due to the complexity of influential factors, such as agricultural management, insect and disease infestations, environmental variability (Marten, 1988; Berzsenyi and Dang, 2008). Environment × cropping system interactions (E × C) are considered as important sources of year-to-year variation in crop yields, and some statistical approaches have been introduced to interpret the interaction in plant breeding research (Crossa, 1990; Kang, 1998). These methods are, in principle, transferable to assess yield stability in agronomic studies (Piepho, 1998).

Long-term experiments (LTEs) are vital for understanding changes in yield, assessing management effects on soil properties and identifying sustainability of cropping systems (Varvel, 2000; Fan et al., 2005; Zhang et al., 2009). Raun et al. (1993) and Grover et al. (2009) evaluated long-term fertilization and crop rotation effects on yield stability by regression approach, and pointed out that LTEs are also valuable for providing the information of interactions between environments and cropping systems. Recently, the additive main effects and multiplicative interaction (AMMI) analysis model, combining the analysis of variance (ANOVA) and principal component analysis (PCA), has been considered as a powerful analytical tool to interpret the E × C interaction and widely employed in breeding research (Zobel et al., 1988; Gauch, 2006). In

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* Corresponding author. Tel.: +86 24 83970421; fax: +86 24 83970366.
E-mail address: iae_yfxh@yahoo.com.cn (W.-T. Yu).

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present study, we try to analyze yield stability under various fertilization treatments/meteorological conditions using AMMI model.

Although mineral fertilizers were applied widely, limited information is available on the effects of mineral fertilization and crop sequence on corn yield stability, and also the relationships between the soil fertility properties/meteorological factors and yield performance. We conducted a consecutive 18-year experiment in northeastern China to (i) investigate the long-term effects of fertilization and crop sequence on corn yield and soil fertility properties; (ii) assess these effects on yield stability and the yield trends; (iii) identify the relationships between soil fertility properties/meteorological factors and corn yield performance.

2. Materials and methods

2.1. Experimental site, design, and treatments

A long-term field experiment has been conducted since 1990 in the Shenyang experimental station of ecology of Chinese Academy of Sciences (41°32′N latitude, 123°23′E longitude) in Liaoning province, which has the longest history of agriculture in northeastern China. Corn is the main crop and there are about 2.1 million ha of corn fields in this region, accounting for 55% of all the arable land (Bureau of Statistics of Liaoning province, 2009). The annual precipitation is about 680 mm, and the mean precipitation is about 520 mm in the corn growing season (Fig. 1). The soil of the experimental field is an Alfisol, the main soil type for agricultural production in the region. Soil texture of 0–20 cm depth is silt loam (sand 289.1 g kg^{-1}, silt 501.1 g kg^{-1}, clay 203.8 g kg^{-1}). The soil was used for rice cropping before the start of the experiments. Analysis of soil samples taken from the experimental area in April 1990 indicated that the initial soil fertility properties of 0–20 cm depth from the surface were as follows: pH 6.5, soil organic carbon (SOC) of 12.3 g kg^{-1}, total nitrogen (TN) of 1.13 g kg^{-1}, total P (TP) of 0.44 g kg^{-1}, total K (TK) of 16.4 g kg^{-1}, soil available N (AN) of 97.3 mg kg^{-1}, available P (AP) of 10.6 mg kg^{-1} and available K (AK) of 88.0 mg kg^{-1}.

The experiment was a two-factorial complete-block design. The eight main plots (each 486 m^2) carried eight fertility regimes, and each main plot was split into three sub-plots (each 162 m^2) carrying the three different phases of a three-course rotation, soybean (*Glycine max*), 1st corn, 2nd corn (S–C–C) with three replicates (9 m × 6 m), so that each phase of the rotation was represented in the field every year. The first corn was thus in a soybean–corn sequence (SC) and the second corn was in a corn–corn sequence (CC). Eight fertilizer combinations were used in the experiment, including unfertilized control (CK), N, P, K, NP, NK, PK, and NPK treatments. Fertilizers, in the form of urea, triple super phosphate, and potassium sulfate, were applied to corn to provide 150, 25, and 60 kg ha^{-1} year^{-1} of N, P and K, respectively. All P and K fertilizers and 40 kg ha^{-1} of N were basal-applied prior to sowing and 110 kg ha^{-1} of N was top-dressed at the stem elongation stage. For soybean, the nitrogen rate was 25 kg ha^{-1} year^{-1}, and P, K fertilizers applied at the same rates as those for corn. N, P and K fertilizers were basal-applied in the spring before sowing. The field was ploughed to a depth of 15–20 cm by horses in spring and pesticides and fungicide were applied when needed during the growing season. Irrigation and herbicides were not applied and weeds were removed by hand-hoeing. Crops were harvested manually close to the ground with sickles in autumn, and yields of both grain and stalk were recorded. Grain and stalk samples were oven-dried at 70 °C to a uniform moisture level and weighed. All harvested biomass was removed from the plots. History corn yield in the region (1970–2007) derived from Bureau of Statistics of Liaoning province (2009).

2.2. Soil sampling and analysis

Every year since 1990, soil sampling has been conducted at a depth of 0–20 cm in autumn. Five soil samples were collected from each replication and mixed to form a composite sample from that replication. The samples were air dried, ground through a 2-mm sieve, and stored for analysis. Soil TP, TK, AN, AP, AK and pH were determined by the methods: TP (molybdenum method), TK (flame photometer method), AN (alkaline-hydrolyzation method), AP (Olsen method), and AK (1 mol L^{-1} ammonium acetate extraction, flame photometer method), pH (1:2.5, soil/H_2O). All the methods are described in detail by Lu (2000). An Elementary vario EL III elemental analyzer was used to determine the SOC and TN.

2.3. Stability analysis

Analysis of the effects of treatments and crop sequence on stability was carried out by AMMI analysis. AMMI calculates treatment and test year additive (main) effects using ANOVA first and then analyzes the residual from this model (interaction) using PCA (Gauch and Zobel, 1988). The AMMI model equation is:

$$y_{ij} = \mu + \alpha_i + \beta_j + \Sigma_n \lambda_n \gamma_{in} \delta_{jn} + \rho_{ij} + \varepsilon_{ijn}$$

where, y_{ij} is the yield of *i*th treatment in *j*th test year; μ is the grand mean, α_i the treatment deviation from grand mean and the test year deviation β_j. λ_n is the Eigen value of PCA axis *n*; γ_{in} and δ_{jn} are the treatment and test year PCA scores for PCA axis *n*; ρ_{ij} is the residual of AMMI model and ε_{ijn} is the random error. The interaction principal component analysis axis (IPCA) provides indicator of stability to assess response of both treatments and test years. The absolute value of first IPCA scores represented the simplest measure of yield stability. For further describing stability using AMMI analysis, the distance of interaction principal component point with origin in space (*D*) and AMMI stability value (*ASV*) were calculated according to Zhang et al. (1998) and Purchase et al. (2000), respectively.

2.4. Aridity index analysis

For exploring the relationship between the meteorological conditions and yield performance in various test years, the potential evapotranspiration during the growing period was estimated using FAO Penman–Monteith equation (Allen et al., 1998), as shown in Fig. 1. Aridity index (AI) is calculated as follows:

$$\mathrm{AI} = \frac{\text{Potential evapotranspiration}}{\text{Precipitation}}$$

In addition, the relative aridity index (RAI) was used to represent the humidity of test year, namely the absolute value of difference between AI and unit. The meteorological data were measured at a weather station close to the experimental farm over the study period (1990–2008), and the history data derived from Liaoning Province Meteorological Bureau.

2.5. Statistical analysis

Principal component analysis of the meteorological data set and AMMI analysis were performed using SPSS 13.0 and Data Processing System (DPS) 9.5 (Tang and Feng, 2007), respectively. The yields of corn grain were analyzed by the analysis of variance (ANOVA) followed by Duncan's multiple range test for multiple comparisons of paired means of treatments at the 0.05 significance level.